Integrating remotely sensed and ancillary data sources to characterize a mountain pine beetle infestation

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Mountain Pine Beetle Initiative
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Abstract

The ongoing mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in British Columbia, Canada, has reached epidemic proportions, with the beetle expanding into geographic areas outside its known biological range. In this study, estimates of red attack damage were derived from a logistic regression model using multi-date Landsat imagery and ancillary information, including terrain attributes and solar radiation. The model estimates were found to be approximately 70% accurate using an independent set of beetle survey data as validation. This probability surface of red attack damage, along with forest inventory and terrain attributes, were used as inputs to decision tree analyses, in order to identify which forest attributes were associated with stands that had a greater likelihood of mountain pine beetle red attack damage. Three distinct decision tree models were developed, each having a different set of input variables. The results of the analyses indicated that site index (an indicator of the quality of a forest site) and slope were the principal discriminators of the current mountain pine beetle attack, followed by basal area of pine-dominated stands, and to a lesser extent, crown closure and stem density. The results suggest that indicators of site quality, particularly site index, could be a complementary addition to existing stand susceptibility rating models.

Keywords: mountain pine beetle, red attack, susceptibility, decision tree, Landsat, Enhanced Wetness Difference Index (EWDI)

Résumé

L'infestation de dendroctones du pin ponderosa (*Dendroctonus ponderosæ* Hopkins) qui sévit actuellement en Colombie-Britannique, au Canada, a atteint des proportions épidémiques; ces coléoptères commencent à se propager dans des zones géographiques qui se trouvent au-delà de leur habitat biologique connu. Dans la présente étude, on a mesuré l'ampleur des dommages causés au stade rouge d'infestation au moyen d'un modèle de régression logistique alimenté par des images LANDSAT prises à des dates différentes et des données secondaires, notamment les caractéristiques topographiques et la radiation solaire. Les mesures fournies par le modèle se sont avérées justes à environ 70 %; elles ont été validées à l'aide d'un ensemble de données indépendantes sur le dendroctone obtenues par relevé. Comme intrants pour effectuer des analyses d'arbres de décision, on a utilisé les probabilités concernant ces aires à risque de subir des dommages au stade rouge d'infestation, des données d'inventaire forestier et des caractéristiques topographiques de manière à déterminer quelles caractéristiques forestières étaient associées aux peuplements forestiers présentant un plus grand risque de subir des dommages à ce stade d'infestation. On a élaboré trois modèles d'arbre de décision distincts comportant chacun un ensemble différent de variables. Les résultats des analyses indiquent que l'indice de station (un indicateur de la qualité d'une station forestière) et la pente sont les principaux discriminateurs des infestations de dendroctones du pin ponderosa, suivis par la surface terrière des peuplements à haute concentration de pins et, dans une moindre mesure, la fermeture du couvert forestier et la densité des tiges. Les résultats montrent que des indicateurs de qualité des stations, particulièrement les indices de stations, pourraient constituer un élément complémentaire aux modèles actuels d'évaluation de la vulnérabilité des peuplements forestiers.

Mots clés : dendoctrone du pin ponderosa, stade rouge d'infestation, vulnérabilité, arbre de décision, LANDSAT, technique de l'EWDI

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Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is one of the most destructive insects in western North America (Wood 1963, Safranyik et al. 1974, Wood and Unger 1996). Generally, the most severe infestations occur in mature stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. latifolia Engelm.), but other pines, such as ponderosa (*Pinus ponderosa* Dougl. ex Laws) and white (*Pinus monticola*, Dougl. ex D. Don) are also attacked. The area affected by the beetle in British Columbia, Canada, has increased from an estimated 165 000 ha in 1999, to approximately 8.5 million ha in 2005 (British Columbia Ministry of Forests and Range 2005). A major factor that has contributed to the successful expansion of the beetle population are the relatively large contiguous areas of mature and over-mature lodgepole pine forest, which have tripled in the last century as a result of intensive fire-suppression activities (Taylor and Carroll 2004). In addition, several successive years of favorable climate (e.g., warmer than average winters) have resulted in an increase in areas climatically suitable for brood development and a buildup of populations in areas that were previously considered unsuitable (Carroll et al. 2004).

The primary host, lodgepole pine, experiences extensive mortality when attacked by mountain pine beetle. Once killed, but still with green foliage, the host tree is in the green attack stage, which occurs in the fall or early winter following initial attack (Safranyik et al.1974). At the commencement of the next growing season (i.e., March), the damage is more visually apparent as foliage becomes chlorotic and ultimately necrotic, changing from light green to yellow, and then from yellow to red (Amman 1982). This is the red attack stage, with trees exhibiting significant chlorophyll degradation as the foliage dies (Murtha 1978). Trees that have been dead for more than a year and have shed the majority of their needles are referred to as gray attack (Unger 1993, British Columbia Ministry of Forests 1995).

Several data types and methods are used to detect and map mountain pine beetle attack, including field-based individual tree assessments (Henigman et al. 1999), aerial surveys from helicopter or small aircraft (see Ciesla 2000 for a review), and digital remotely sensed satellite imagery (Wulder et al. 2004a). The extent of a survey may range from a few hectares to millions of hectares (Wulder et al. 2004a). Conventional forest health monitoring in British Columbia involves broad-scale reconnaissance from aircraft with manual interpretation and delineation of affected stands onto 1:100,000 or 1:250,000 maps (Wulder et al. 2006a). These maps are used primarily for strategic planning, identifying areas requiring more intensive survey, allocating mitigation resources, and adjusting the allowable annual cut and timber supply forecasts (British Columbia Ministry of Forests 2003a, British Columbia Ministry of Forests 2003b). Detailed surveys of beetle populations are conducted in order to expedite deployment of field crews to areas eligible for suppression activities or requiring sanitation harvesting. Surveys at this scale are typically completed using a helicopter with a global positioning system (GPS), with which the infestation locations, the number of trees, and their attack stage are recorded (Wulder et al. 2004a).

Digital satellite remote sensing offers a complementary methodology for the detection and mapping of mountain pine beetle attack with benefits that include capacity to cover large spatial area, thereby ensuring a systematic census—rather than a sample—of forest stands (Wulder et al. 2006a). In addition there is often a reduction in interpreter bias through application of automated delineation methods (White et al. 2004), which can increase the consistency and reliability of mapping between different areas or dates (Coops et al. 1998, Wulder et al. 2004b). Combining remote sensing observations with other ancillary geographic data such as digital terrain information and other relevant meteorological information allows influence of topographic and solar radiation attributes to be included when estimating mountain pine beetle attack (Wulder et al. 2006b).

Recent outbreaks of mountain pine beetle above long-term endemic levels provides opportunity to investigate those particular stand attributes or conditions that lead to an increase in likelihood to be mass attacked by the mountain pine beetle. The objectives of this analysis were two-fold:

- to demonstrate if multi-date satellite imagery can be used to detect mountain pine beetle infestation at a regional scale;
- to determine, retrospectively, which forest inventory attributes are associated with new mountain pine beetle infestation.

Methods

To meet these objectives, a logistic regression model was developed using multi-date Landsat remotely sensed imagery. The output of the model was an estimate of the likelihood of beetle damage across the study area. The accuracy of this probability surface was then assessed using existing forest health survey data.

Decision tree, also known as Classification and Regression Tree (CART; Breiman et al. 1984) analysis was then used to identify which forest attributes were associated with stands that had a greater likelihood of mountain pine beetle red attack damage. Decision trees are rule-based approaches that generate a model through binary recursive partitioning, a process that splits a node based on yes/no answers about the values of the predictors. Decision trees are increasingly being applied to land-cover mapping (Pal and Mather 2003), vegetation and habitat modeling (Guisan and Zimmermann 2000), soil surveys (Scull et al. 2005), and forest health modeling (Negron and Popp 2004, Sims et al. 2006). The approach requires a single dependent variable (e.g., probability of red attack trees) and multiple independent variables (such as forest inventory information or other environmental data). The result of a decision tree analysis is the generation of rules that correspond to "branches" of the decision tree, which maximize the class purity within each of the two resulting subsets. The strength of the approach is that it provides a method to encapsulate a range of variables (such as categorical and continuous) in an understandable and coherent structure (Simard et al. 2000).

Three distinct decision tree models were developed using different combinations of the input variables: (i) using forest inventory data alone; (ii) using a combination of inventory and other geographic data, and; (iii) using only a subset of variables most often used in susceptibility mapping and the results of the analysis highlighted those attributes, such as age, site quality, crown closure, or species composition, which associated with an increased likelihood of red attack damage. These rules and the identified attributes would complement existing susceptibility ranking systems such as the Shore and Safranyik model (1992), and subsequently enhance our current understanding of susceptibility of forest stands to attack by mountain pine beetle.

The Study Area

This research was undertaken within Tree Farm License (TFL) 48, managed by Canadian Forest Products Ltd (Figure 1). TFL 48 covers approximately 650 000 ha and is located in northeastern British Columbia near Chetwynd (55.70° N, 121.63° W). The elevation of TFL 48 ranges from 220 m to 3000 m above sea level. The primary forest types within the region include high-elevation forests dominated by Engelmann spruce (*Picea englemannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hooker)), mid-slope forests dominated by hybrid spruce (*Picea glauca* (Moench) Voss subsp. *engelmannii* (Parry ex Engelmann)) and lodgepole pine, and boreal foothills and plains dominated by mixed stands of white spruce (*Picea glauca* (Moench) Voss) and lodgepole pine (Seely et al. 2004).

Figure 1: Location of TFL 48 study area.

Data

In order to undertake this study, four sets of data were used: multi-date satellite imagery covering the period of infestation; ancillary information including a digital elevation model (DEM) and associated derived attributes (e.g., solar radiation); inventory polygons describing forest stand attributes over the region; and information on the current distribution of mountain pine beetle infestation from ground and aerial survey plots.

Landsat Image Time Series

Research has demonstrated that Landsat Thematic Mapper ™ imagery, with 30- spatial resolution may be used at the landscape scale to accurately detect mountain pine beetle red attack damage (Franklin et al. 2003, Skakun et al. 2003, Wulder et al. 2006b). When the spectral Landsat channels are re-projected along the principal directions of brightness, greenness, and wetness (known as a Tasseled Cap Transformation (TCT); Kauth and Thomas 1976, Crist and Cicone 1984, Crist et al. 1986), information can be gathered on forest mortality, disturbance, and anthropogenic change. Price and Jakubauskas (1998) found that stands in Yellowstone National Park were distinguishable using TCT components when the overstorey was progressively thinned as a result of beetle damage. Similarly, Sharma and Murtha (2001) demonstrated that there were significant differences in the TCT between lodgepole pine stands in British Columbia attacked by the mountain pine beetle and stands not attacked. Franklin et al. (2003) used an automated detection algorithm (as opposed to a visual interpretation) on a 30-m Landsat TM image. This study detected clusters of red trees smaller than 0.2 ha with a resulting classification accuracy of 73.3% (based on 360 independent mountain pine beetle field- and aerial-survey validation points). Skakun et al. (2003) used multi-date Landsat-7 Enhanced Thematic Mapper (ETM+) imagery acquired on three separate dates. The TCT wetness index for each date was thresholded and an enhanced wetness difference index (EWDI) was used to interpret spectral patterns in stands with confirmed red attack damage. The classification accuracy of the red attack damage based on this type of transformation ranged from 67% to more than 78% correct (Skakun et al. 2003). Wulder et al. (2006b) generated a probability surface of red attack damage from a logistic regression model that incorporated EWDI, elevation and slope. Assuming a 50%

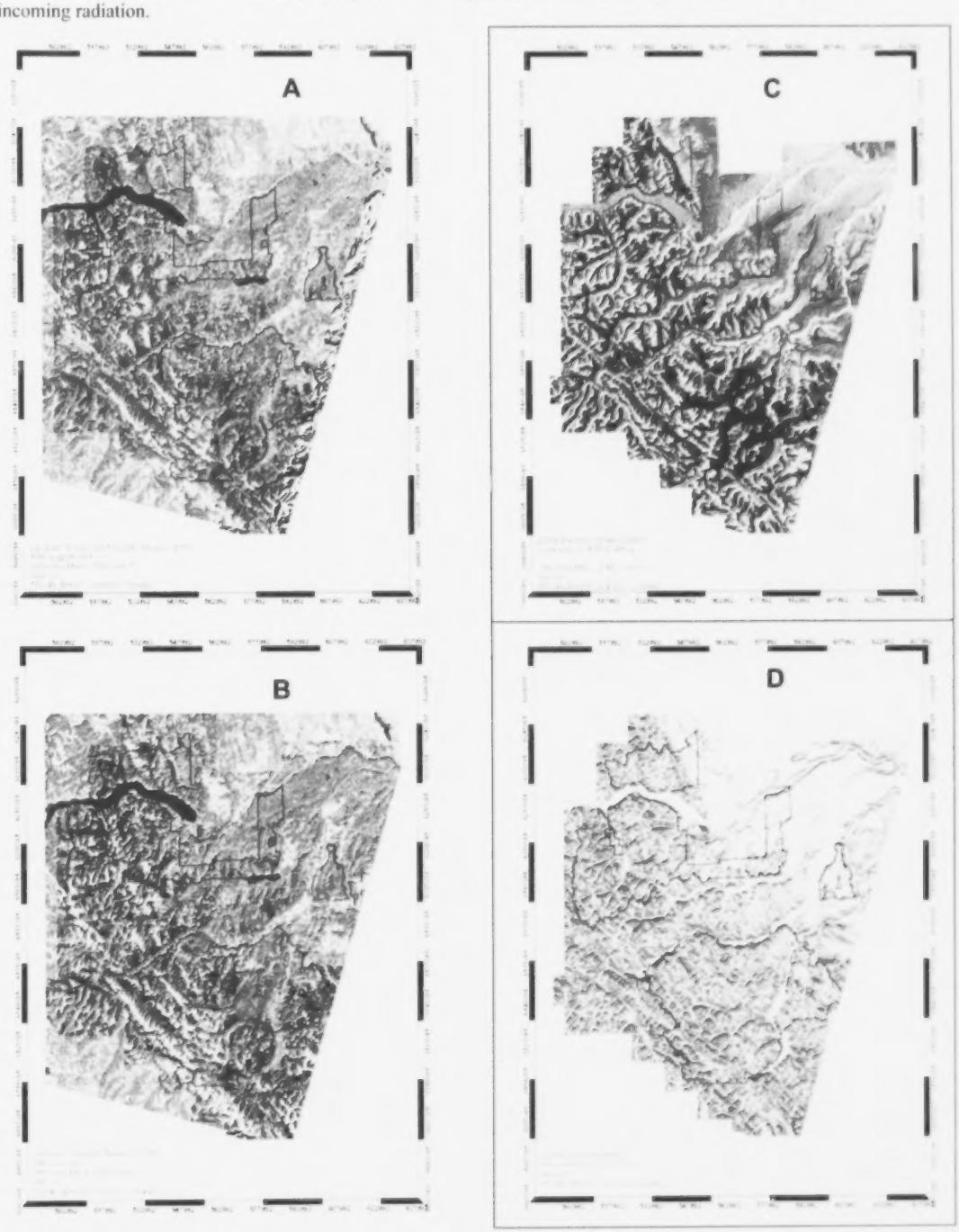
threshold (> 50% likelihood of attack = red attack), red attack damage was mapped with an accuracy of 83%.

A time-series of Landsat imagery was acquired that corresponded to pre- and post-infestation time periods in the study area. The pre-infestation image was acquired by the Landsat-7 ETM sensor on August 16th, 2001. The post infestation image was acquired by the Landsat-5 TM sensor on July 29th, 2003 (both images were Path 49, Row 21). The two images were orthorectified to a UTM projection using base maps and a 30-m Digital Elevation Model (DEM; described below) with a resulting root mean square error of less than 0.5 pixel (using a third-order polynomial transformation and cubic convolution resampling algorithm). The image scenes covered 544 000 ha or approximately 80% of the TFL. A top-of-atmosphere correction was applied to both images to correct for the appropriate gain and offsets unique to each of the sensors and convert them to top-of-atmosphere reflectance (Markham and Barker 1986). This correction accounts for differences in sensor and viewing geometry, but does not correct for variations in absolute atmospheric conditions between images. The 2001 and 2003 Landsat scenes are shown in Figures 2(a) and 2(b) respectively.

Ancillary Data and Associated Derived Attributes

In addition to the remotely sensed imagery, a 30-m DEM was available over the study area (British Columbia Ministry of Sustainable Resource Management 2002b). From the elevation model, long-term annual diffuse and direct radiation surfaces were derived following the methods of Kumar et al. (1997), which compute the potential solar radiation based on latitude, terrain and Julian day. The technique takes into account overshadowing by high peaks; meaning that the routine detects cells that are in the shadow of adjacent terrain for high sun positions, making it highly suitable for applications with variable terrain. The Compound Topographic Index (CTI) (unitless) was also calculated to provide an indication of soil moisture status (Moore 1991), based on up-slope contributing area and terrain slope. Higher values of CTI tend to be found at the lower parts of watersheds and in convergent hollow areas associated with soils of low hydraulic conductivity (Beven and Wood 1983). The CTI is considered indicative of soil depth, silt and clay content, and water content capacity. Both the radiation and CTI surfaces were used in the model development to determine if additional ancillary information (such as site and meteorological factors) could provide explanatory power to the prediction of mountain pine beetle attack. Figure 2 (c) and (d) show the DEM of the region, with aerial and field locations of mountain pine beetle infestation and the estimate of annual direct radiation over the region.

Figures 2 (a) to (d): Landsat Thematic Mapper ™ and Enhanced Thematic Mapper (ETM) true color composite images for the TFL 48 region in (a) 2001 and (b) 2003 respectively; (c) Digital Elevation Model (DEM) of the study area overlaid with 2004 aerial and field survey of mountain pine beetle attack and (d) estimation of direct total incoming radiation.



Forest Inventory Database
In 2001, 1:40,000 aerial photography was flown over TFL 48 and forest stands manually delineated by trained interpreters. Stands were attributed and digitized according to Vegetation Resources Inventory (VRI) standards (British Columbia Ministry of Forests 1998). Each forest stand was delineated as a separate polygon and labeled with a unique identification number and a series of attributes such as species composition (as many as six species were recorded for each stand), age (in years), total stand basal area (m2 / ha) and canopy closure (in 5% intervals) (British Columbia Ministry of Sustainable Resource Management 2002a). From these variables, using standard statistical forest growth curves, the site index, an indicator of site quality, is estimated. Site index is the most widely used measure of site productivity (Carmean 1975) and is based on the height of the dominant trees in a stand at an arbitrarily chosen age. In British Columbia site index is defined as the height of a site tree at 50 years breast height age. A site tree is the tree of a given species with the largest diameter at breast height on a 0.01-ha plot (Stearns-Smith 2001). As no mountain pine beetle infestation was present at the time the photography was flown in 2001, there was no beetle-attack information for any of the forest stands in the area associated with the VRI coverage.

Detailed Surveys of Mountain Pine Beetle Damage
Locations of stands with mountain pine beetle damage were collected from aircraft observations and ground surveys from March to June, 2004. Aerial observations of red attack damage were located by a trained observer in a helicopter; a GPS location was recorded for each infested stand along with the number of damaged trees in three classes: red attack (trees with red crowns), gray attack (dead trees with no needles), and yellow/green (trees changing color from green to red). Given the recent nature of the infestation, the majority of trees in the study area were either classified as red or yellow/green attack. A field program was undertaken subsequent to the helicopter survey and a series of 0.25 ha plots were established within forest stands identified as having red attack damage. The numbers of infested trees in these plots were recorded using the same classification system as the helicopter survey and the tree locations were recorded using GPS. In total, 740 heli-GPS and field plots were located over the entire TFL region covering all stages of attack; of these, 437 plots represented locations of known red attack damage where located within the study area. The sample plots with red attack damage were extracted to a separate data set to be used in the calibration and validation of the Landsat estimates of red attack damage.

Phase 1: Estimating the Likelihood of Mountain Pine Beetle Red Attack Damage

Enhanced Difference Wetness Index (EWDI)
A TCT (Tasselled Cap Transformation) was generated from each of the calibrated Landsat TM and ETM images (wetness coefficients are shown in Table 1), resulting in a brightness, greenness, and wetness image for each image. The EWDI was then calculated by subtracting the 2003 wetness image (post-infestation) from the 2001 wetness image (pre-infestation). Positive EWDI values represent a decrease in moisture between 2001 and 2003; this decrease in moisture has been found to correlate to mountain pine beetle red attack damage (Franklin et al. 2003, Skakun et al. 2003, Wulder et al. 2006b), as foliage subject to red attack damage will be considerably drier in 2003 than in 2001, when compared to non-red attacked foliage.

Table 1: Coefficients / weightings of Landsat TM and ETM bands to generate "wetness" index.

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
ETM	0.263	0.214	0.093	0.066	-0.763	-0.539
TM	0.151	0.197	0.328	0.341	-0.711	-0.457

Extraction of Red Attack and Non-red Attack Stands

Forest health surveys rarely collect data for areas not damaged by disease or insects. Furthermore, since aerial and ground surveys are generally not conducted systematically across the landscape (with exceptions including the aerial overview sketch mapping program in British Columbia), it is not valid to assume that those areas not included in the survey represent areas of healthy forest. Therefore, a critical step for modeling location of red attack damage, in the absence of this survey information, was to locate stands where red attack damage was not evident. Including these sites ensures model validation as well as estimation of errors of commission and omission associated with the detection of red-attack damage (Wulder et al., 2004a). In the absence of aerial photography or other suitable high spatial resolution data (collected at the same time as the post-infestation Landsat data), an image-based source of calibration and validation data was considered the best alternative. A sample of non-attacked stands was generated by calculating the greenness component of the TCT for the 2003 Landsat image. The greenness component of the TCT indicates the abundance and vigour of the vegetation cover (Crist and Kauth 1986, Dymond et al. 2002, Gong et al. 2003, Healy et al. 2005), and is designed to be orthogonal from the other TCT components (Wulder et al. 2006b). The assumption was made that pixels having high greenness values would be less likely to contain large numbers of red attack trees. A random set of 450 pixels with high greenness values was extracted from lodgepole pine stands (as identified in the forest inventory). When combined, the non-red attack and red attack samples represented 887 locations (450 non-red attack and 437 red attack locations). Approximately 15% (N = 136) of the total samples were reserved for use in the assessment of model performance.

Model Development

A logistic regression approach was used to relate the binary (red attack / non-red attack) ground data to the continuous variables, resulting in a probability surface of red attack based on significant independent variables (Wulder et al. 2006b). A forward stepwise selection approach was applied to establish which of the input independent variables, (EWDI, elevation, long-term annual direct and diffuse radiation, and CTI) were the most significant for predicting the occurrence of red attack damage. Significance was assessed using the Wald statistic (Dobson 1990), which was computed as the generalized product of the parameter estimates using the respective variance–covariance matrix. The significance of the Wald statistic was then tested against the chi-squared distribution. Once developed, the model was applied to the reserved 15% of survey observations to assess model performance.

Phase 2: Characterizing the Likelihood of Mountain Pine Beetle Red Attack Damage with Forest Inventory Attributes

After the probability surface of red attack damage was developed, the degree of damage within each forest stand could be compared to inventory attributes for the same region. Polygon decomposition was used to obtain the average likelihood of red attack damage (as estimated by the logistic regression model) for each inventory polygon (Wulder and Franklin 2001, Wulder et al. 2005). Only polygons where pine was the leading species, as defined in the inventory, and where the polygon area was greater than nine TM pixels (0.8 ha) were included in the analysis. The nine pixel threshold was chosen to reduce cases of small polygons consisting solely of boundary cells. Mean values for CTI, slope (in degrees), and elevation within each inventory polygon were also extracted for each stand. In total, approximately 15 000 individual inventory polygons met the size and dominant species criteria for inclusion in the analysis. The attributes estimated from the forest inventory are shown in Table 2.

Table 2: List of attributes obtained from forest inventory polygon database (Vegetation Resources Inventory).

INVENTORY ATTRIBUTE:	DESCRIPTION:
CROWN CLOSURE	Crown closure (%)
SITE INDEX	Site Index (m)
AGE	Mean Age of Stand
HEIGHT	Mean Height of Stand (m)
SPECIES1	Code of Primary species in stand
SPERCENT1	Composition (%) of primary species in stand
SPECIES2	Code of Secondary species in stand
SPERCENT2	Composition (%) of secondary species in stand
SPECIES3	Code of Tertiary species in stand
SPERCENT3	Composition (%) of tertiary species in stand
QUADRATIC DIAMETER (PRIMARY)	DBH (cm)
CUMULATIVE MAI	Mean Annual Increment (cm)
BASAL AREA	Basal Area of stand (m2 / ha)
DENSITY	Number of live stems per hectare (stocking)
SNAGS	Snag frequency in stand
HABITAT	Vertical complexity

A decision tree model was then used to determine the relationship between the likelihood of a forest stand having red attack damage and the forest inventory and terrain attributes associated with these stands. Decision tree models were developed using CART (version 5) (Breiman et al. 1984) in regression-tree mode, facilitating identification of natural groups within continuous data using a least-squares splitting method. The program was limited to creating a small number (8) of classes, as the objective of this research was to identify general rules to assess the inventory attributes. Additional classes were removed if they contained a small number of stands or if the difference in stand red attack damage between each class was small. Three distinct decision tree models were developed: (i) the first developed was based on forest inventory attributes for each inventory polygon; (ii) a second was then produced based on the structural and terrain information for each polygon, and: (iii) a third model, which used only the attributes included in the Shore and Safranyik (1992) mountain pine beetle susceptibility rating system (discussed below).

Phase 3: Comparing the Likelihood of Red Attack Damage to the Shore and Safranyik Susceptibility Model

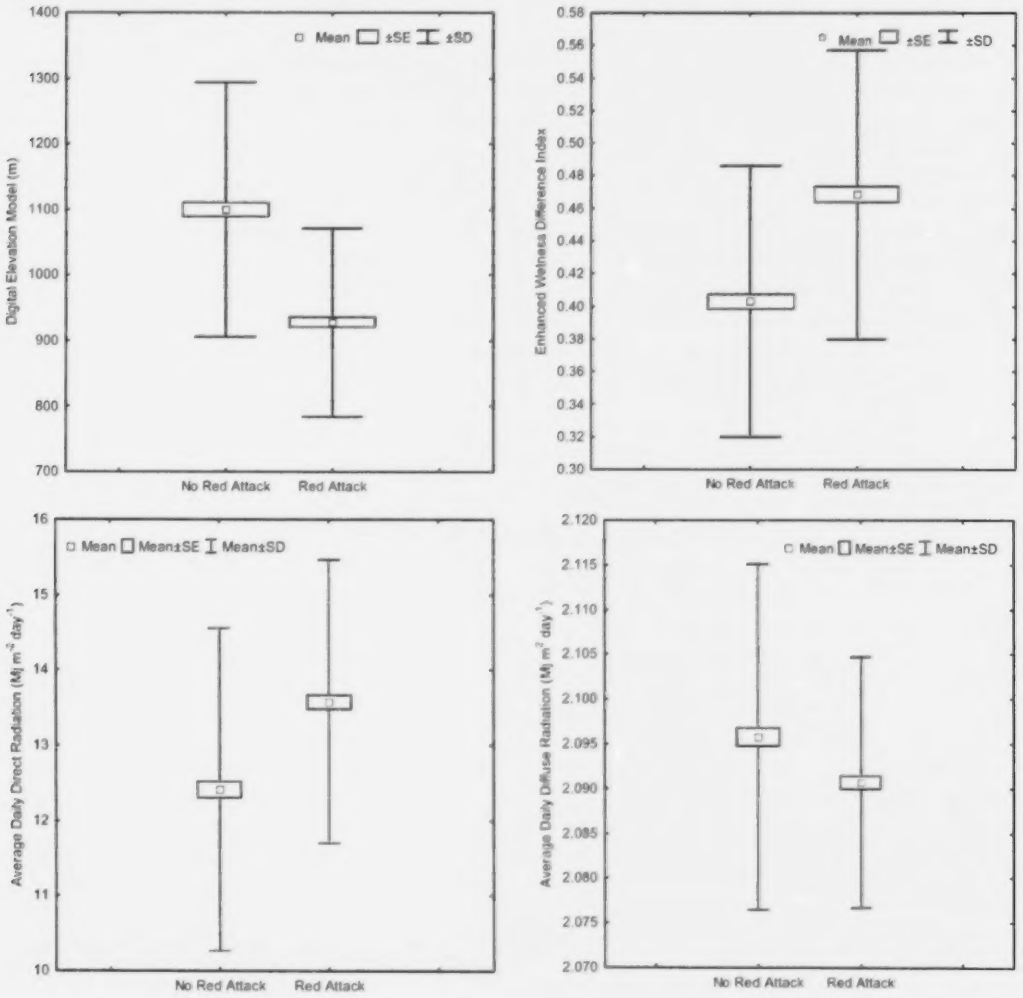
A number of models exist for estimating stand-level susceptibility and risk of attack by mountain pine beetle (Amman et al. 1977, Mahoney 1978, Berryman 1978, Schenk et al. 1980, Waring and Pitman 1985, Anhold and Jenkins 1987). The Shore and Safranyik (1992) susceptibility rating model, commonly applied in British Columbia (Shore et al. 2000), is one of the few models that incorporates spatial information (Bentz et al. 1993). This susceptibility rating provides a useful comparison to our probability surface of red attack damage. The model is based on four factors: stand pine basal area; age of the stand; number of stems; and locational information (longitude, latitude, and elevation). Stands are deemed to be highly susceptible if pine are between 80 and 120 years old, stem density is moderate (750 to 1500 stems per hectare), and elevations fall within a specific range. Each factor is scaled between zero and one, and summed to produce a total score. Susceptibility ratings provide an indication of forest stand conditions that may be favourable to beetle attack; however, they do not predict where beetles will attack. The latter is estimated through risk ratings, which combine susceptiblity with knowledge of the size and location of beetle populations, and are developed to provide an indication of the short-term loss in stand basal area (Shore and Safranyik 1992, Bentz et al. 1993). Risk rating systems accurately predicted risk in stands that were infested; however, not all of the high-risk stands were subsequently attacked (Dymond et al. 2006). In our study, percent of susceptible pine basal area within each inventory polygon was not available, only total stand basal area and the species composition for up to the first six species recorded in each stand were. As a result, we used the percent of pine in each pine-leading stand as a surrogate for percent of basal area of susceptible pine. In addition to a visual comparison between the probability of occurrence of red attack damage derived from the stepwise logistic regression approach and the stand susceptibility score based on the Shore and Safranyik (1992), a 1-km grid was placed over the study area, and 1 465 were samples extracted from both layers to allow a quantitative comparison.

Results

Phase 1: Estimating the Likelihood of Mountain Pine Beetle Red Attack Damage

Of the four spatial datasets (EWDI, DEM, long-term annual diffuse radiation and direct radiation) the DEM and EWDI show the greatest capacity to differentiate the presence of red attack, followed by direct, and then diffuse radiation (Figure 3). All variables have some degree of overlap between classes; however, general trends indicate stands without red attack correspond to lower EWDI values, increased elevation, reduced direct solar radiation, and increased diffuse radiation. An analysis of variance (ANOVA) indicates all four datasets are statistically able to separate the two classes at $p < 0.01$ level.

Figures 3 (a) to (d): Mean and standard error and deviation box and whisker plots of the four spatial attributes (Digital Elevation Model (DEM), Enhanced Difference Wetness Index (EDWI), direct and diffuse radiation) grouped by field plots and aerial sites with mountain pine beetle infestation, and stands estimated as healthy with no mountain pine beetle infestation.



The results of the stepwise logistic regression approach indicate that three of the four input variables (elevation, EWDI, and direct radiation) were highly significant ($p < 0.01$) in identifying the presence of red attack damage, based on the field and heli-GPS plots (Table 3). Using the remaining 15% of observations not used in the model development as an independent assessment, the overall accuracy of the model for both the non-red attack and red attack trees was 68% with a similar true-positive classification rate (Kohavi and Provost 1998) for red attack damage of 69% (Table 4). This level of accuracy is comparable to that achieved in previous studies that have applied the EWDI approach (Franklin et al. 2003, Skakun et al. 2003, Wulder et al. 2006b). The overall accuracy provides a general indication of the accuracy of the outputs if all classes were of equal importance. Each individual class has two measures of accuracy: producer's and user's. The producer's accuracy is the percent of reference sites for a particular class that were correctly classified during the remote sensing process. In this model, 69.01% of the attacked trees in the study were identified by the model. The corollary of the producer's accuracy was the omission error: the number of reference sites for a particular class that were omitted from the remotely sensed class (30.99%). The user's accuracy is the percent of model estimates that were correctly classified (70.00%). The corollary of the user's accuracy was the commission error: the number of reference sites for a particular class that were erroneously included in a particular class. The most useful single indicator of accuracy for red attack is the user's accuracy for the attack class, also known as the true-positive rate (Kohavi and Provost 1998).The estimation of red attack damage was considered sufficiently accurate to justify the application of the logistic model to the entire study area. As a result, a probability surface was generated for the study area, using EWDI, DEM, and radiation inputs. Values in the surface ranged from 0 to 1, with each 30 m by 30 m pixel area having an associated probability of red attack damage.

Table 3: Output of logistic regression model estimating the likelihood of mountain pine beetle red attack damage generated from Landsat wetness difference index, DEM, and diffuse and direct radiation estimates.

	DF	Estimate	Standard Error	Wald Statistic	Significance
All Attacked Trees					
Intercept	1	-0.878	0.898	0.957	0.328
DEM	1	0.005	0.001	78.527	0.000
Direct Radiation	1	0.000	0.000	10.213	0.001
EWDI	1	-4.528	1.482	9.337	0.002

Table 4: Accuracy assessment confusion matrix for the red attack damage estimates using a reserved set of 150% of the heli-GPS survey data (N = 136). For the purposes of the accuracy assessment, a 50% likelihood threshold was used to identify red attack (> 50%) and non-red attack (≤ 50%). The overall accuracy is the percent of correctly classified sample points (e.g., 68.84%).

n=138		MODEL ESTIMATED				
		Not Red	Red	Total	Producers	Omission
FIELD ESTIMATED	Not Red	46	21	67	68.66%	31.34%
	Red	22	49	71	69.01%	30.99%
	Total	68	70	68.84%		
	Users	67.65%	70.00%			
	Commission	32.35%	30.00%			

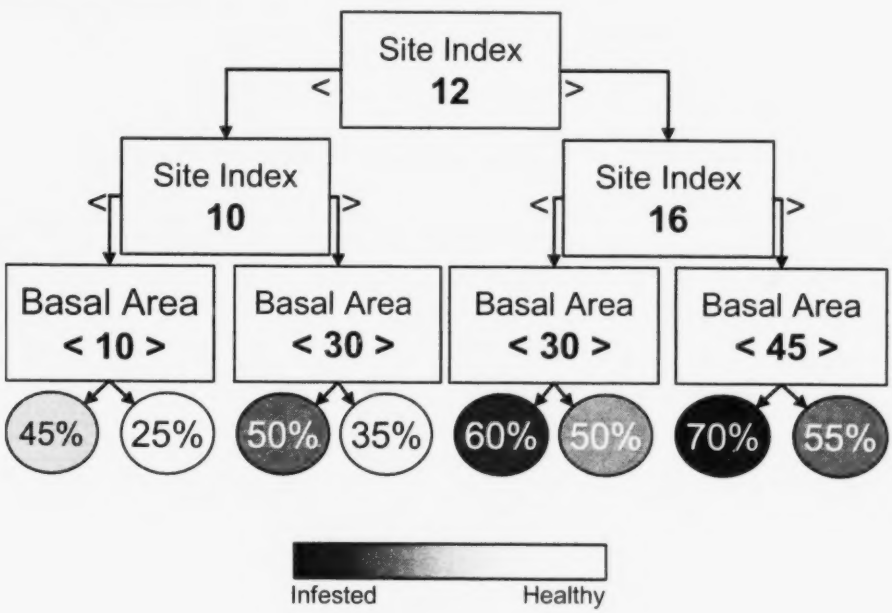
Overall Accuracy	68.84%	True negative rate	68.66%
True positive rate	69.01%	False negative rate	30.99%
False positive rate	31.34%	Precision	70.00%

Phase 2: Characterizing the Likelihood of Mountain Pine Beetle Red Attack Damage with Forest Inventory Attributes

In the first decision tree model (Figure 4), site index and basal area of pine-leading inventory polygons provide the most effective stratification of the dataset. Generally, the model indicates that pine stands with site index less than 12 m were estimated to have a lower likelihood of red attack damage than stands with site indices above 12 m. Stands with site indices less than 10 m and basal areas greater than 10 m^2 / ha have the lowest probability (25%) of red attack damage. Conversely, stands with site indices greater than 16 m and stand basal areas less than 45 m^2 / ha have the greatest probability of red attack damage (70%). Stands with the lowest productivity (site indices less than 10 m and basal areas less than 10 m^2 / ha) had a moderate likelihood of red attack damage (45%); this is similar to stands with the highest productivity (site indices greater than 16 m and basal areas greater than 45 m^2 / ha) (50%).

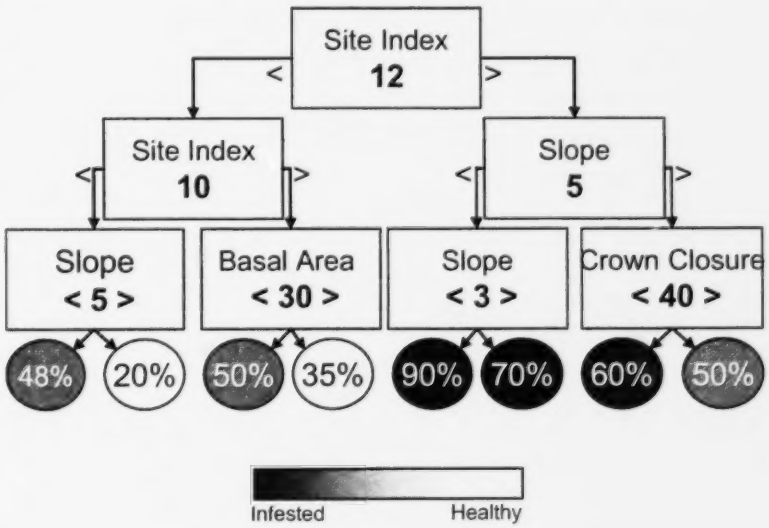
In addition to basal areas of pine-dominated stands, other forest attributes were correlated to stands with red attack damage, although these attributes were less significant than basal area. For example, at the lower site indices, canopy closure, age and density were all selected as possible alternative splitters to basal area, indicating that these could equally be used to differentiate presence of red attack damage. Conversely, for stands with higher site indices, crown closure less than 60% provided an alternative to discriminating increasing likelihood of red attack damage.

Figure 4: CART Regression tree model for pine-dominated stands estimating red attack from forest structural information derived from the inventory polygons. If stands have attributes less than the specified value at each decision tree node, the next decision to the left is invoked. Alternatively, if the stand attributes are greater than the specified value, the next decision node on the right is used. Note that rules are applied additively: for the second set of decisions, the first decision is still applied.



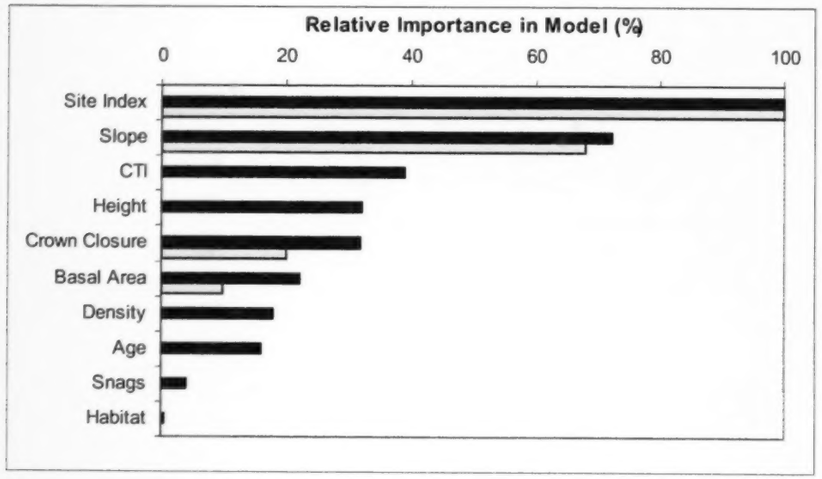
A second model was developed using the same forest inventory structural data as the previous model, with the addition of ancillary terrain attributes (slope and CTI) (Figure 5). Site index was the most significant variable for identifying stands that had a greater likelihood of red attack damage in this model as well; however, slope was also an important secondary discriminator. In the low site index stands (site index < 10 m), steeper slopes (> 5°) are estimated to have a low likelihood of red attack damage (< 20%). Conversely, stands with site indices greater than 12 m and shallow slopes (less than 3°) have a 90% probability of red attack damage, and stands with site indices greater than 10 m and slopes between 3° and 5° have a 70% probability of red attack damage. Finally, stands with site indices greater than 12 m on steeper slopes (> 5°) are also estimated to have a greater likelihood of red attack damage (> 50%), with crown closure providing an additional discriminating level.

Figure 5: CART Regression tree model for pine-dominated stands estimating red attack from forest structural information and terrain information derived from the inventory polygons.



The relative importance of the input variables to the first and second decision tree models is indicated in Figure 6. Interestingly, site-quality factors, including site index, slope, and CTI, were the most important variables for model performance (as estimated using the least-squares regression approach within CART). Site index explains the majority of the variance in all models, followed by the average slope. Crown closure, followed by basal area of pine-dominated stands, also provided some additional explanatory power in the developed models, as could height, density, and stand age, if slope, basal area, and site index were unavailable.

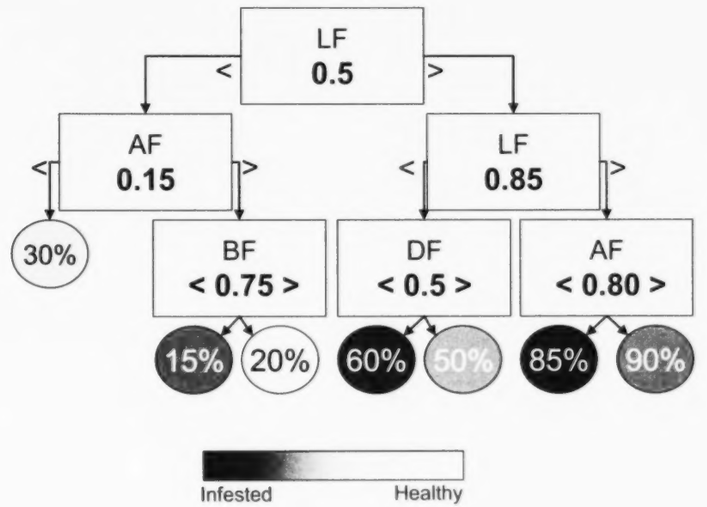
Figure 6: Relative importance of the inventory structural and terrain attributes. Two sets of results are shown. Gray bars display the relative importance for the variables used in the first two models. Black bars indicate the overall relative importance of each variable, taking into account possible substitutions of variables with similar explanatory power.



Phase 3: Comparing the Likelihood of Red Attack Damage to the Shore and Safranyik Susceptibility Model

The third decision tree model was generated using the four Shore and Safranyik (1992) susceptibility rating factors: basal area factor (BF), age factor (AF), density factor (DF), and location factor (LF). Each of these factors has values that range from 0 to 1. The results of this decision tree model indicate that the location factor is most important for identifying areas with a greater likelihood of red attack damage (Figure 7). If the location factor is high (i.e., > 0.85), then the age factor provides additional discrimination in identifying stands with a greater likelihood of red attack damage (90%). Conversely, stands with a lower likelihood of red attack damage have a low location factor (i.e., < 0.5), combined with an age factor > 0.15 and a basal area factor less than 0.75 (i.e., mixed species stands).

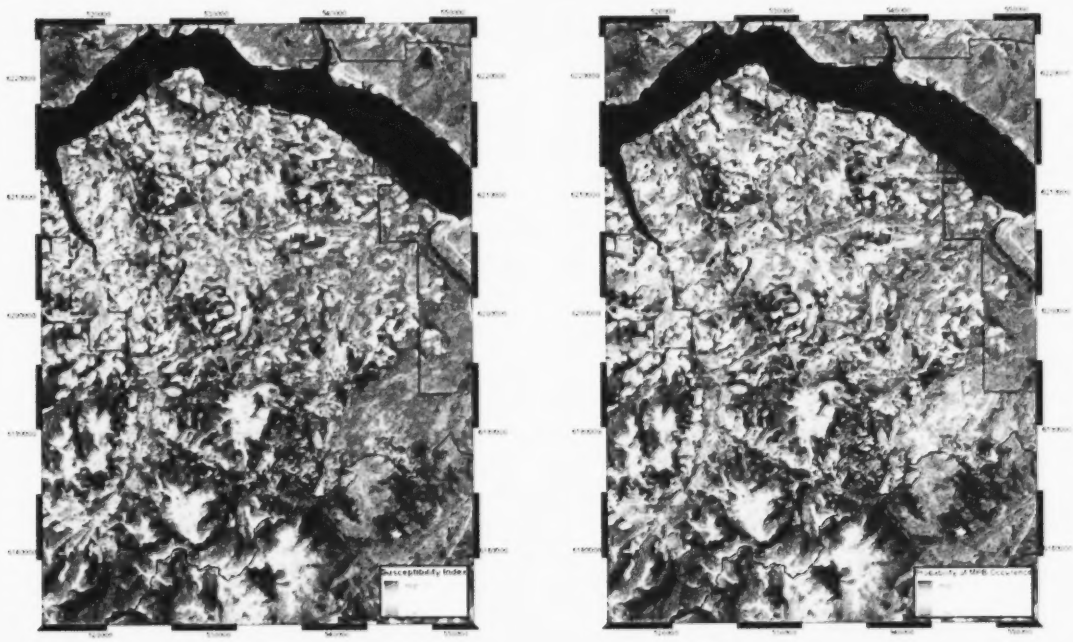
Figure 7: Diagrammatic representation of CART Regression tree model for stands derived from the four factors of the Shore and Safranyik (1992) susceptibility ranking system (LF: location factor; AF: age factor; DF: density factor; BF: basal area factor).



The Shore and Safranyik (1992) susceptibility rating was calculated for the study area and compared to the probability surface generated from the logistic regression model. Both the susceptibility rating and the probability surface indicate that areas along valley bottoms have a greater susceptibility to, and likelihood of, red attack damage (Figure 8), while lower susceptibility to, and probability of, red attack damage was found at high elevations and along ridge tops. The movement of the beetle through the landscape along the valley bottoms is more evident on the logistic regression estimated probability of red attack, than on the susceptibility rating system.

Figure 8: (a) Probability of red attack trees as derived from the GLM model; (b) the susceptibility rating developed by Shore and Safranyik (1992) for a subset of the TFL 48 region.

(a): (b):



The relationship between the cells extracted from the probability of occurrence of red attack damage derived from the stepwise logistic regression and cells with a stand susceptibility score greater than 0 is strongly positive, with cells that have an increased susceptibility also exhibiting a high probability of attack. Likewise, cells with low susceptibility levels are associated with reduced probabilities of attack. Although these two indices cannot be directly compared, as the susceptibility score is based simply on the presence of selected forest inventory attributes within set ranges, where as the probability of attack is based upon actual remote sensing observations, the strong correspondence between the two indicates the stepwise regression model predicts attack in accordance with expectations.

Discussion

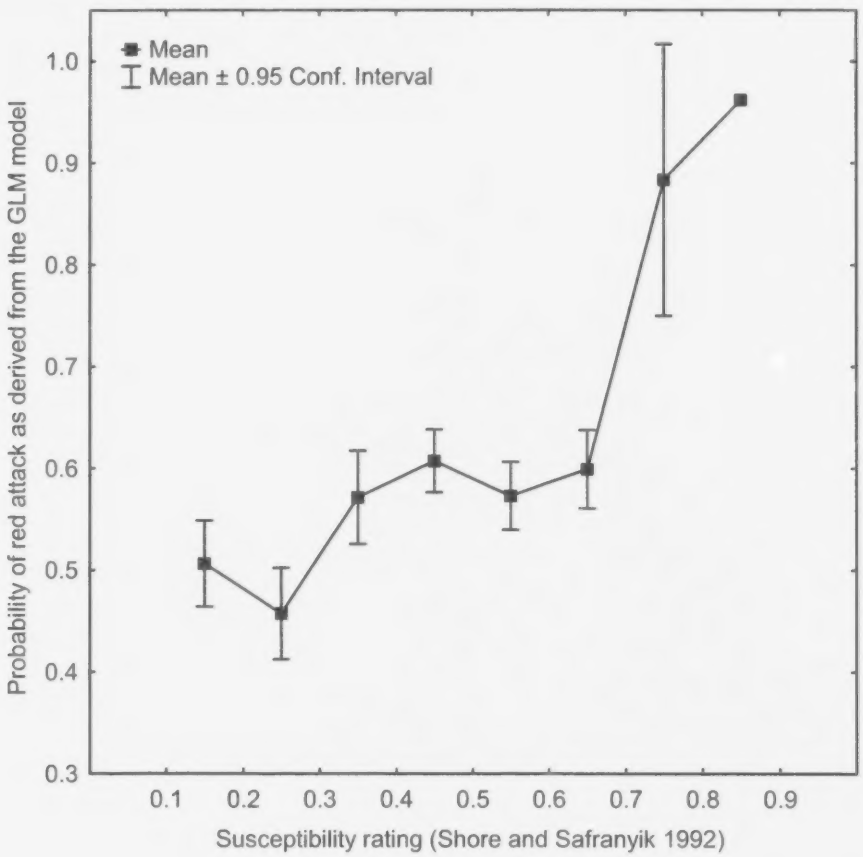
The multi-date TCT-transformed wetness images captured the likelihood of mountain pine beetle red attack damage with 70% accuracy, which is comparable to the accuracies obtained using similar methods in other geographical areas (Franklin et al. 2003, Skakun et al. 2003, Wulder et al. 2006b). However, a requirement in any analytical method to detect mountain pine beetle red attack, and subsequent validation and accuracy assessment, is to have access to accurate spatial locations for both red attack and non-red attacked trees. Targeted surveys of beetle red attack damage (e.g., heli-GPS surveys), such as the one used for validation in this study, produce data which can be biased to locations of known mountain pine beetle attack rather than providing a systematic survey of red attack and non-red attack stands. The lack of verified non-red attack stands makes the development of analytical models more difficult, as the location of non-red attack trees has to be inferred, possibly introducing error into the model outputs. Field-based information on the location of healthy forest should be collected and included in future modeling applications as these strengthen the power of infestation models.

The logistic regression model was developed using a combination of spectral and topographic information. The inclusion of radiation data in the model is logical due to the increased likelihood of attack in forest stands that are experiencing stress, particularly moisture stress (Safranyik 2004), and the importance of temperature to beetle survival (Safranyik 1978). The final logistic regression model incorporated the EWDI, elevation and radiation; this differs from the results of Wulder et al. (2006b), in which EWDI, elevation and slope are identified as critical variables for estimating the likelihood of red attack damage in a study area in Montana, USA. The difference between these two models may be linked to the more northerly location of TFL 48, which is almost 10° latitude further north than the Montana study site.

A benefit of a CART modeling approach is that it can be applied under conditions where ordinary least-squares–based regression cannot. For example, as the decision tree approach does not rely on any a priori statistical assumption, it is suitable for classifying categorical and/or continuous data, such as remotely sensed and ancillary information including elevation and climate information (Simard et al. 2000). Decision trees deal with these two types of data more effectively than standard regression-based approaches do. In addition, decision trees that provide a logical rule pathway that describes the decision and makes the model suitable for intuitive understanding can also reveal hierarchical and nonlinear relationships among input layers (Fries et al. 1998). However, an issue with the decision tree analysis (as with most empirical approaches) is that it provides no discriminatory power outside the range of the input data, with the developed rules only suitable for datasets with equivalent ranges. Therefore, decision trees require input data that are completely representative of the actual data set in order to produce meaningful rules.

The VRI contains a broad range of attributes, some of which are interpreted directly from air photos or measured by ground sampling. Many other VRI attributes are subsequently derived from these measured attributes or are modeled using established relationships. As a result, many attributes in the inventory may be correlated (e.g., diameter at breast height and volume), although, since many of these attributes describe different components of the forest stand, they still may have discriminatory power for the decision tree analysis. Unfortunately, not all of the VRI attributes are populated for every forest stand, limiting the ability to use the full suite of possible inventory attributes in the decision tree. In this research, only a subset of the available attributes, representing the major structural definitions of forest stands, were selected for input to the decision tree analysis. Further research could be undertaken on additional VRI attributes if there was an a priori indication that these may provide additional discriminating power.

Figure 9: Categorized relationship between: X axis: Levels of stand susceptibility based on rating system developed by Shore and Safranyik (1992) for a subset of the TFL 48 region (0 is no stand susceptibility and 1 is high stand susceptibility) and Y axis: Probability of red attack trees as derived from the GLM model (0 is low probability of attack, 1 is high probability of attack).



Three different decision tree models are presented in this research; the two models developed using the forest inventory and terrain attributes exhibited similar and consistent trends. The results of all three models confirm that site-specific variables, such as site index and slope, are important for discriminating sites with a greater likelihood of red attack damage (Figure 9). Other important variables that appeared in both models include site index, basal area of pine-dominated stands, and crown closure. In general, the results of the decision tree analyses using the forest inventory attributes indicated that stands with a high probability of red attack damage were characterized by:

- site indices greater than 16 m and basal area of pine dominated stands less than 45 m^2 / ha; or,
- site indices greater than 16 m and slopes less than 5°.

A high site index value indicates that the site is of high quality (Carmean 1975). A high-quality, pine-leading site with a lower-than-expected amount of basal area could suggest that stand was experiencing some sort of stress (e.g., drought), which would generally make it more susceptible to attack by mountain pine beetle. The fact that these trees may have been experiencing stress

makes them more vulnerable to beetle pioneers, who upon arriving in the study area, unlikely would have had the same level of success in attacking non-stressed hosts (Logan et al. 1998). Alternatively, the stand could have been thinned (intentionally or by some form of natural disturbance), resulting in stand-density conditions that were not as suitable to the beetle (Safranyik et al. 1974). Desirable hosts (e.g., older pine with thicker bark) are commonly found on the high-quality sites in relatively flat terrain, making the pine in these areas ideal host candidates for beetle.

Conversely, forest stands with a low probability of red attack damage were characterized by:

- site indices less than 10 m and basal area of leading pine stands > 10 m^2 / ha; or
- site indices less than 10 m and slope greater than 5°.

Low-quality, pine-leading sites on steeper slopes would likewise typically have unsuitable hosts for brood establishment.

Of the four factors from the Shore and Safranyik (1992) susceptibility rating system that were used in the third decision tree model, the location and age factors were the most important in describing the current distribution of red attack trees in the TFL 48 study area. The least important discriminator of the current attack was the density factor, which only differentiated minor differences in attack level. The location factor includes longitude, latitude, and elevation; its importance in identifying stands with a greater likelihood of red attack damage further emphasizes the importance of site-quality factors.

The Shore and Safranyik model uses the proportion of total basal area that is susceptible pine (e.g., proportion of basal area that is pine greater than > 15 cm dbh) as one parameter in the determination of a stand's susceptibility rating. Given the unprecedented nature of the mountain pine beetle infestation within the TFL 48 study area, combined with the lack of knowledge concerning the characteristics of the trees in this area that are being successfully attacked by mountain pine beetle, the percent of the stand with pine limited to pine-dominated stands was used in this analysis rather than make assumptions regarding what constitutes susceptible pine and its proportional basal area within the study area. Although basal area was an important discriminator in the first decision tree model, the degree to which other forest attributes (i.e., crown closure) could be used as surrogates for basal area to generate similar results suggests that the importance of basal area in this analysis is not as relevant for future analyses as site-quality factors such as site index and slope.

The importance of site index for identifying stands with greater likelihood of red attack damage indicates that an indicator of site quality could be a useful addition to a susceptibility rating system. Oneil (2005) found that stand-stocking thresholds for mountain beetle outbreak, as reported in the literature, vary significantly by site quality. This implies that site index may be a useful means of stratifying forest stands prior to estimating susceptibility, in order to better capture the variation in site quality. The natural variability in lodgepole pine stands across British Columbia has been documented in the literature (Wu and Ying 2004, Wu et al. 2005). Given the inherently complex relationship between lodgepole pine and mountain pine beetle, this variability in the host species will in turn have implications for the beetle (Bentz et al.1993). A site-specific variable such as site index could further emphasize the spatial nature of the beetle population.

A potential management response to this information could be to use the site-index attribute contained in the forest inventory to stratify the landscape before applying a susceptibility rating model, with some adjustment factor then potentially applied to each strata. Another option may be to develop some means of incorporating site index as a separate factor in a model similar to that of Shore and Safranyik (1992). A third option would be to apply an adjustment after susceptibility ratings have been generated, using an empirical relationship between the rating and the site index value. Regardless of the approach used to incorporate site index, further research would be necessary to investigate the relationship between site index and susceptibility ratings across the spatial range of the current mountain pine beetle outbreak. The motivation for finding some

means to incorporate site-quality factors into the susceptibility rating would be to enhance the identification and prioritization of susceptible stands for treatment or sanitation harvesting.

Site index has successfully been modeled using a combination of physiological and growth and yield models (Swenson et al. 2005, Wang et al. 2005), while basal area and crown closure can be estimated using aerial photography (Oswald et al. 1999) and potentially also with high-resolution satellite data (Wulder et al. 2004c). Given the value of these indicator attributes and the multiple data sources available for their estimation, in conjunction with the large range of available pine (in British Columbia and beyond into the boreal forest) and the current expansion trend of the natural biological range of the mountain pine beetle, there is potential for the integration of this information into a system of pre-emptive monitoring for mountain pine beetle in pine forests.

Conclusion

The objective of this study was to characterize the attributes of stands with a greater likelihood of sustaining red attack damage resulting from an infestation of mountain pine beetle in an area of British Columbia that has traditionally been outside the beetle's biological range. A probability surface indicating the likelihood of red attack damage across the study area was generated from a multi-date Landsat imagery and other attributes, and was found to be approximately 70% accurate, using independent validation data. The probability surface was compared to stand susceptibility ratings generated by the Shore and Safranyik (1992) model. Generally, high susceptibility was found to correspond with greater likelihood of attack. The probability surface was then input as a dependent variable into three distinct decision tree models, with several forest and terrain attributes as independent variables. Attributes related to site quality, including site index and slope, were found to be most informative at identifying areas of red attack damage. The results suggest that indicators of site quality, particularly site index, would be a complementary addition to existing stand susceptibility rating models. This study also demonstrated that remotely sensed data can be a valuable source of information for identifying areas of red attack damage on the landscape, and that this information can subsequently be used as inputs to models designed to characterize the nature of the infestation and ultimately improve management response to mountain pine beetle outbreaks.

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